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ANALYSIS OF THE UNITED STATES NAVY UNIFORM INVENTORY CONTROL PROGRAM AND A PROPOSED REPAIR/PROCUREMENT INTERFACE MODEL

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THESIS

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AND A
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by

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Uniform Inventory Control Program
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Proposed Repair/Procurement Interface Model

by

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ABSTRACT

The U.S. Navy inventory control of repairable items at the Inventory Control Point level is accomplished with the aid of the Uniform Inventory Control Program. This paper analyzed the existing Uniform Inventory Control Program's implied repairable model. Also, the nature of a Repair/Procurement Interface for management of repairable items was analyzed. Under a "substitution policy" and a "cyclic system repair requirements determination" assumption, characteristics of the interface were noted and principles of operation were developed. From these principles, a proposed model was conceived which provides equations and decision rules to obtain procurement and repair policies.

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TABLE OF SYMBOLS AND ABBREVIATIONS

a	fixed demand
a'	protectable war reserve material
A	order cost
α	customer attrition
ASO	Aviation Supply Office
B08	UICP application Cyclic Repairables Management
B10	UICP application Supply Demand Review
bt	demand which is a linear function of time (t)
β	one minus carcass repair survival rate
C	procurement cost
CARES	Computation and Research Evaluation System
CR	NRFI carcasses in commercial repair
CRTAT	commercial repair turn-around-time
CSRRD	cyclic system repair requirement determination
$\underset{\sim}{d}$	is distributed
D05	UICP application Levels Computation
DOP	designated overhaul point
δ_t	state variable, if Q_p is to be received in time t, $\delta_t = 1$, otherwise, $\delta_t = 0$
ESO	Electronics Supply Office
$f(X_{SRR})$	density of system repair requirements
$H(X_{ATT(t)})$	complementary cumulative of attrition in time t
ICP	Inventory Control Center
I	inventory holding cost rate
INDD	induction delay
λ_{ATT}	average annual attrition

LOR	Level of Repair
$\mu_{W(t)}$	mean of random variable W in time t
NICRISP	Navy Integrated Comprehensive Repairable Item Scheduling Program
NR	NRFI carcasses in Navy repair
NRFI	not ready for issue material
NRTAT	Navy repair turn-around-time
$\mathcal{N}(\mu,\sigma^2)$	distribution of a normally distributed random variable, mean μ, variance σ^2
PLT	procurement lead time
π	shortage cost
Q_p	economic order quantity
r_p	procurement reorder level
RFI	ready for issue material
RSL	repair safety level
RTAT	repair turn-around-time horizon
SDR	Supply Demand Review
SPCC	Ship's Parts Control Center
SRR	system repair requirements
$\sigma^2 W(t)$	variance of random variable W, in time t
UADPS	Uniform Automated Data Processing System
UICP	Uniform Inventory Control Program
WCR	carcasses to be shipped to commercial repair
WNR	carcasses included on induction candidate list
X	gross system random demand
X_{SRR}	random system repair requirements
X_t	gross random demand in time t
Z_t	random regenerations in time t

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I further wish to acknowledge B. F. Skinner's appropriate representation of knowledge, from Waldon Two.

> "I do not say that John or Jonathan will realize this, but such is the character of that morrow which mere lapse of time can never make to dawn. The light which puts out our eyes is darkness to us. Only that day dawns to which we are awake. There is more day to dawn. The sun is but a morning star!"

I. INTRODUCTION

Inventory systems supporting technical equipment usually distinguish between repairable and consumable items. A repairable item is so designated because when it fails, instead of being scrapped, it is returned to a queue, or waiting line, for repair and subsequently returned to serviceability. The decision to classify an item as repairable is based upon the technical feasibility of repair and relative economies of repairing the item vice buying a new one. The economies of repair include both lower cost of repair than of procurement and generally shorter repair turn-around-times than procurement lead times. The Navy uses a three level of repair (LOR) concept. The levels of repair are organizational, intermediate and depot. This paper was not concerned with classification of inventory items or LOR decisions which are assumed determined.

The analysis was, however, concerned with Inventory Control Point (ICP) establishment of repairable item policies. These policies include when and how much to repair at the depot level, and when and how much to procure. The Navy ICP's, Aviation Supply Office (ASO), Ships Parts Control Center (SPCC) and Electronics Supply Office (ESO) use depot level repair at Naval Air Rework Facilities (NARFs), Navy Shipyards and commercial contractors.

Recent Navy history is marked by cut-backs in men, money, and material resources. Yet, high strength and responsiveness

needs require better management and utilization of available resources. In a limited resources environment effective inventory control of repairable material is essential. A small improvement in ICP repairable item inventory control represents a great potential impact on resource utilization. Only seven percent of Navy controlled items are repairable but they represent eighty-five percent of Navy inventory stores account material.

Two primary facts generated interest in a Navy repairable system analysis. Firstly, two disturbing observations about the performance and effectiveness of the existing Uniform Inventory Control Program (UICP) model, in applied real-world terms, were reported. The first observation was that repair quantities were being generated which were ignored by the ICP commodity managers. The second observation was that, despite declining budgets, procurement buy quantities, for repairables, were causing system long supply. It was hypothesized that procurement decisions were being made independently without knowledge of repair assets.

The second interest generating fact was that UICP application B08, Cyclic Repairables Management, was recently included in the UICP system. B08 implementation organizationally acknowledged a need to fix problems in the Repair/Procurement Interface. In fact, as analysis showed, an invalid assumption ("batch" repair), implied by the Levels Computation application D05, was resulting in an inadequate model of the real-world system.

The objective of the analysis was two-fold. First, a Repair/Procurement Interface analysis of the model, implied by the existing UICP equations and decision rules, was undertaken. This analysis established the apparent inadequacy of the current UICP mechanism to model the Navy's cyclic repair system and to effect an appropriate timing of repair and procurement decisions. Second, an effort was made to model the Repair/Procurement Interface adequately. Several principles for management of the Repair/Procurement Interface were developed. Finally, decision rules for the applied model were generated. The proposed model is consistent with current UICP Supply Demand Review (SDR), application B10, techniques and with Cyclic Repairable Management, application B08, decision rules.

Section II presents results of analysis of the existing UICP model.

II. ANALYSIS OF THE EXISTING UICP MODEL

Department of Defense Instruction (DOD) 4140.11 of June 1958 marked the beginning of "scientific inventory control" in the Navy. The instruction directed the use of "statistical techniques and proven economic principles" in management of DOD activity inventory systems. Coupled with this directive there was a strong requirement within the Navy to establish uniformity in organization, management and procedures among its several ICPs and stock points. Out of these needs, the Uniform Automated Data Processing System (UADPS) was conceived. UADPS today is a computer system using the latest hardware, standard programs and procedures capable of performing various functions at the unique ICPs. The Uniform Inventory Control Program (UICP), which is the UADPS ICP level computer program, controls the provisioning, technical, financial, cataloging, purchasing and inventory control functions. The last two functions were analyzed by this study. The UICP purchase and repair control functions have been implemented since 1965, hence sufficient operational experience exists to evaluate its adequacy. The final judgement of the UICP model's adequacy to generate sound Repair/Procurement policies lies in the consistency of the policies with real-world operations.

To evaluate the adequacy of policy generated by the UICP repairable model, it was necessary to assimilate three

primary UICP program applications. The first application, D05, called Levels Computation, computes a system reorder level, economic order quantity, attained risk, and units short for the procurement problem. D05 also generates a repair order level, economic repair quantity, repair stock-out risk, and raw units short per repair order cycle for the repair problem. The procurement problem generates procurement policies for consumable and repairable items, while the repair problem only generates repair policies for repairable items.

The second application, B08, Cyclic Repairables Management, replaced the ASO Navy Integrated Comprehensive Repairable Item Scheduling Program (NICRISP), in July 1973. The relevant purposes of the new B08 application are to compute system repair requirements and to create recommended repair schedules. This is done by comparing system requirements and system assets over a repair turn-around-time (RTAT) horizon.

The third application of interest is Supply Demand Review (B10). Application B10 compares system requirements and system assets over a procurement lead time (PLT) horizon and initiates and/or recommends procurement actions for repairable and consumable items.

The above three UICP program applications are described in Supply System Design Specifications (Ref. 2). They are computationally oriented and do not reveal the underlying assumptions or model of the Repair/Procurement Interface.

Also available for reference was ALRAND Report 45 (Ref. 1), which provides minimum documentation on computation of procurement policies while totally ignoring any mention of the repair problem. Hence, it was necessary to hypothesize, from limited available documentation, what the underlying UICP assumptions and model are, as implied by existing computations and decision rules.

The equations in the Levels Computation (D05) procurement problem are derivable from a model referred to by Hadley and Whitin (Ref. 4) as an approximate treatment of the continuous review model. Accordingly, the implied assumptions of UICP procurement computations are continuous review, or a transaction reporting system; stochastic demands with a known distribution; and, a fixed procurement lead time (PLT). Additionally, the total controllable cost, of operating the procurement system is a function of the cost of placing an order, the cost of holding Ready-for-Issue (RFI) material and the cost of shortages. Time-weighted shortages are not considered by the model. The objective of the model is to identify the policy, or in other words, to select the order point and economic order quantity so as to achieve an economic balance between order cost, holding cost, and shortage cost. The optimal balance minimizes total average annual cost of operating the system. To realize this cost minimization the model also assumes knowledge of the relevant costs.

The UICP procurement problem equations imply constraints on the Hadley and Whitin model. For instance, the economic

order quantity is constrained to help satisfy an ICP order frequency constraint and establish an upper and lower bound on investment in a single item procurement. Also, imputed stockout costs are used as a budget execution tool by recomputing them during the fiscal year.

The computations associated with the procurement problem are sound, within organizational constraints, and represent good utilization of the inventory theory available to date.

On the other hand, hypothesizing the model of the repair problem and its interface with procurement is at best non-trivial. The repair problem equations appear to be a "forced" modification of the procurement problem equations. Hence, it was not surprising to find an analogous repair level, quantity, risk and units short. These policies require similar assumptions as in the procurement problem. Thus, continuous review, random demand and a fixed repair turn-around-time are assumed.

The objective function implied by the repair problem is to minimize the total average annual cost of repair. The relevant repair costs differ from the procurement problem costs but are used in a one-to-one correspondence. For example, procurement order cost is replaced by repair administration cost plus repair set up cost, while unit procurement cost becomes unit cost of item repair. The repair problem requires an imputed stockout cost analogous to the imputed procurement stockout cost. Besides being difficult to understand what is implied by a repair stockout,

system experience shows that there does not exist an "analyzer" for this shortage cost similar to the Computation and Research Evaluation System (CARES) analyzer for procurement. Indeed, for ASO, who does not control Navy repair budget, the concept of "budget execution", which requires the imputed stockout cost procedure for procurement, is meaningless for Navy repair.

The "most significant" finding of the analysis of the existing UICP model is that Levels Computation (D05) implies "batch repair". This assumption is documented first, by the existence of an economic repair quantity and second, by the inclusion of a "batch accumulation" time in the procurement turn-around-time. The contention is that the existence of an economic repair quantity and batch accumulation time in D05 is contradictory with the computation methodology of the new Cyclic Repairable Management Application (B08). Application B08, in simple terms, compares expected requirements versus expected assets over the repair horizon and identifies the difference as "system production requirements". The system production requirements, limited to available carcasses, are placed on an "induction candidate" list. The list is ordered by "levels" of need, which are a function of the urgency of the need of the material. For example, level one includes only priority 01-08 backorders identified as: Not Operational Ready Supply; Casualty Reporting; and Ships Essential Equipment Requisition Program backorders. The list is forwarded to appropriate NARFs where the decision of

whether or not and how much to induct is controlled by the NARF, not the ICP. Before arguing that a contradiction in basic assumptions exists, the following discussion of "batch repair" by Richards (Ref. 8) is presented as a frame of reference.

> "In practical situations it is often true that a repair facility is charged with the responsibility of repairing many types of items so that the number of workers available to handle repairs for a single item is limited. Due to the shortage of workers it is frequently not possible to commence the repair of an unserviceable carcass as soon as the carcass enters the repair facility. In addition, it may be more economical not to repair each item individually. For example, the cost of repairing items usually includes a fixed cost which is incurred each time an item is inducted for repair. This fixed cost, which is independent of the number of items inducted, might include the cost of letting a contract or the cost of converting machinery from one job to another job ("set up" cost). If the fixed cost is substantial it would often be more economical to let a batch of items accumulate before the items are inducted for repair. In that way, only a single fixed cost would be incurred for the entire "batch" of items.
>
> Batch repair, on the other hand, has the disadvantage of forcing some items to wait in a queue at the repair facility until service begins. This delay results in increasing the probability of a stockout in the system. Thus, when choosing a repair policy, one should attempt to balance the fixed costs against the cost of backorders."

Richards' discussion of "batch repair" is helpful in identifying the decision criterion for resolving the issue of "batch repair" versus the alternative of the "cyclic system repair requirements determination" (CSRRD) assumption. The decision criterion is whether or not the ICP has organizational control and responsibility for minimizing "fixed costs" of repair or is motivated by the goal of minimizing costs of backorders. The "batch repair"

assumption is consistent with minimizing fixed costs of repair, and the "CSRRD" assumption corresponds to an objective of minimizing costs of backorders. The first point in arguing for a "CSRRD" assumption is that Navy ICPs have no control over the fixed costs of repair. This is apparent, as explained previously, in the case of ASO's relationship with NARFs. It is again obvious for all ICP's commercial repair illuminated by the fact that currently, with few exceptions, manufacturers set up costs are set to zero in the appropriate UICP data element number (DEN). These costs are set to zero because the data is not available. Therefore, it is currently not computationally feasible for the ICP to effectively batch commercial repair. The second, even more convincing argument for the "CSRRD" assumption is that Navy ICP experience, in a limited budget environment, has restricted repair "levels" to the top two. These levels include mostly backorders and some end user planned requirements (representing "certain" backorders if material is not available). Thus, it seems reasonable to assume that the ICP repair program role is limited to cyclically identifying "repair candidates" to minimize backorder cost of "aged" high priority backorders. And so, it is certain that B08 decision rules are grounded in a "CSRRD" assumption, which is more adequate than the D05 batch repair assumption, to model the operational system. Given the assumption of "cyclic system repair requirements determination" as appropriate to model the Navy ICP real-world, it would seem that repair quantities,

generated by D05, are meaningless and so are the computations of repair level and repair risk which are a function of the repair quantity.

To conclude, the analysis of the existing UICP model, as implied by available documentation, shows that there does not exist a Repair/Procurement Interface. Repair and procurement decisions are, in fact, disjoint. Action is necessary to reconcile the difference in basic assumptions of D05 and B08. It appears that a new model must be developed which incorporates the "CSRRD" assumption of B08 and which establishes an interface between the procurement problem and the repair problem. Further, the nature of the required Repair/Procurement Interface must be defined and a model and decision rules must be established to tie together Supply Demand Review and Cyclic Repairables Management. The results of the Repair/Procurement Interface analysis and a proposed model are presented in the next section.

III. THE REPAIR/PROCUREMENT INTERFACE AND A PROPOSED MODEL

The term Repair/Procurement Interface is used to describe three essential parts of repairable item inventory control. First, it refers to the decisions of when and how much to repair; and second, it refers to when and how much to procure repairable items. Finally, the word interface applies to the timing required to coordinate the repair and procurement decisions to accomplish the objectives of maximizing the repairable system effectiveness subject to budgetary and repair capability constraints.

To help understand and analyze the nature of the Repair/Procurement Interface, an iconic, or pictoral, model was developed. A descriptive analysis and principles of the Repair/Procurement Interface are presented in the following section.

A. THE REPAIR/PROCUREMENT INTERFACE

Figure 1, The Repair/Procurement Interface Model, represents the Navy ICP's view of the repairable item management system. The model is described in the following paragraphs by its requirements, assets and scrap sections; relevant problem horizons and associated pipelines; sources of RFI material, including the mechanism of the repair system; and flows of material assets.

Figure 1 is divided into three sections: requirements, assets and scrap. The requirements section identifies four

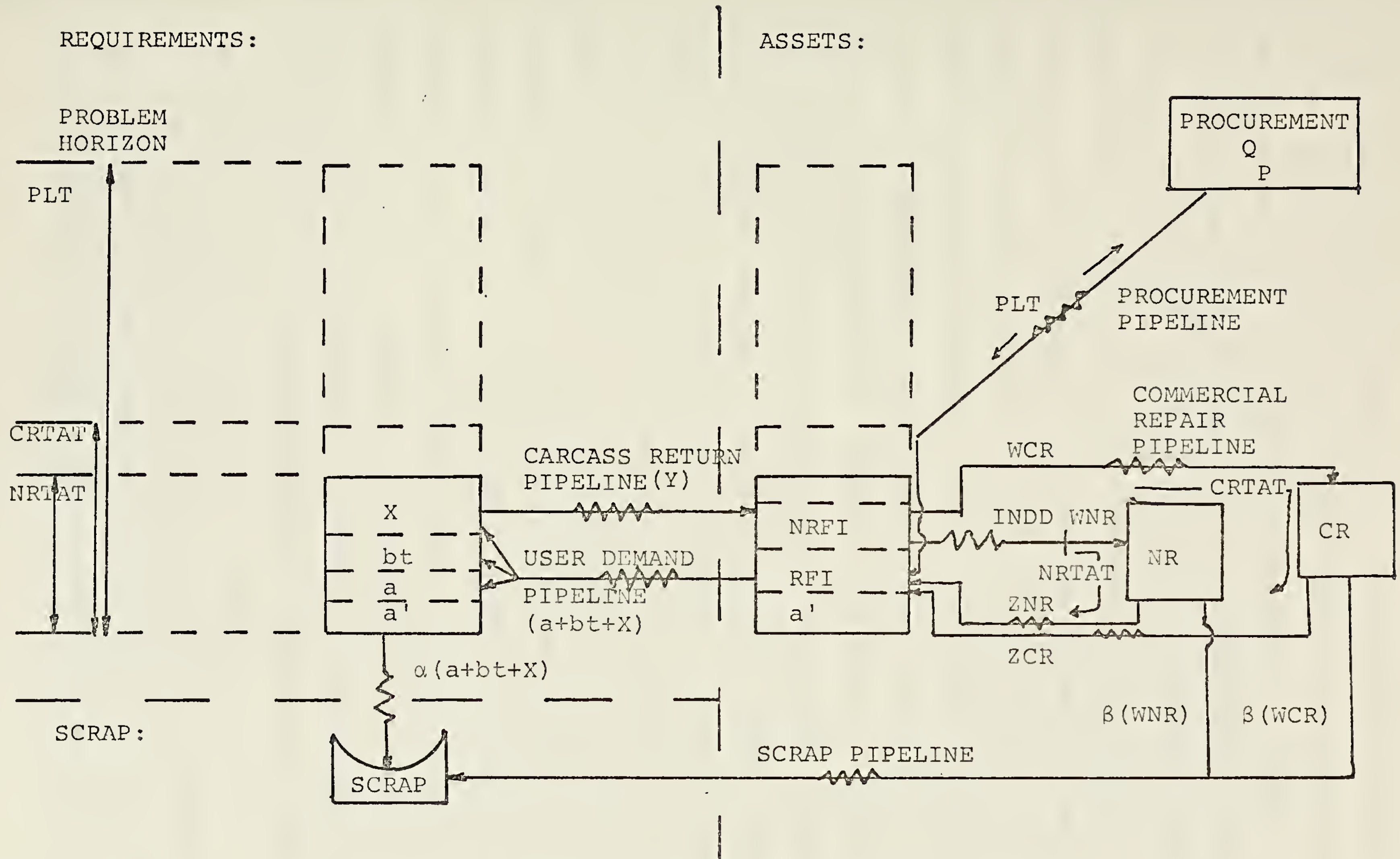

Figure 1. REPAIR/PROCUREMENT INTERFACE MODEL

types of system needs for material. Requirements over any given time horizon are equal to $a' + a + bt + X$: where, a' represents protectable war reserve stocks; a is fixed one time needs during the horizon, such as backorders and scheduled planned requirements; bt is requirements which are a linear (b) function of time (t) such as planned requirements which are due today and everyday; and finally, X is a random variable representing gross system random demand. Assets of the system include RFI and NRFI material. RFI assets include RFI material in Navy stock plus potential carcass regenerations and RFI due-in (Q_p = economic order quantity) from procurement during the horizon. NRFI assets include NRFI carcasses in Navy stock, and NR and CR which, in the diagram, represent carcasses in Navy repair and commercial repair, respectively. Carcasses are assets because of the "opportunity cost" savings they represent, which are equal to the difference between the cost of procurement and the cost of repair. The scrap section represents the material attrition of the system. Attrition includes assets which are lost in transit, and those carcasses which are deemed beyond the capability of maintenance or repair. Decisions to scrap material are made at the customer level as depicted by the arrow coming from requirements and at the Navy or commercial repair facilities.

The Repair/Procurement Interface requires solution of two problems. It was asserted that repair policies should be determined by looking at requirements and assets over a

repair problem horizon. Similarly, procurement policies should be determined by comparing requirements and assets over the procurement horizon. The fact that requirements and assets vary by the time period considered is represented by the dashed lines in figure 1. As depicted in the figure, the repair problem horizon corresponds to the Navy or commercial repair turn-around-time (NRTAT, CRTAT) and the procurement problem horizon corresponds to the procurement lead time (PLT). It is of note that another advantage of a repair system is that RTAT is generally significantly shorter than PLT. There is potential disagreement about what RTAT and PLT should represent. However, the proposed model of this analysis is robust with respect to these definitions. RTAT will be considered as the time from Navy repair induction until system receipt and PLT will be the time from placement of an order for RFI until system receipt.

Procurement from commercial contractor is a source of RFI material. The system can count on this material, Q_p, an economic order quantity, a PLT from the date the purchase is made. Figure 1 shows that RFI material may also be obtained by Navy or commercial repair. It depicts two repair routes. The commercial repair route is characterized by a CRTAT which includes shipment to and from the contractor and a delay for repair of an item. Commercial repair is used by all of the ICPs. The other repair route is Navy repair. SPCC and ESO use Navy shipyards for some repair, but ASO uses NARFs for the large majority of their repair. The

Navy repair route is typified by INDD and NRTAT. NRTAT is the time from physical induction of material by the NARF until receipt in the system. INDD represents induction delay, which is the time from item inclusion on a list of repair induction candidates until physical induction by the NARF, indicated by the INDD pipeline. The appropriate route for repair is initially determined by an item's Source, Maintenance and Recoverability code.

It is important to understand how physical assets flow throughout the repairable system. The user demand pipeline carries RFI assets from stock to fill a, bt, and X type requirements. It is of note that a' protectable requirements do not flow but remain in stock. Carcasses are transported via the carcass return pipeline. In steady state, letting α equal the customer attrition rate, then $(1-\alpha)(a + bt + X)$ material will flow back to NRFI stock. The procurement pipeline carries an economic order quantity from the contractor to RFI stock. The commercial repair pipeline carries shipped carcasses to commercial repair sources and returns them to RFI stock. The Navy repair pipeline carries material from NRFI stock points through Navy repair and back to RFI stock. Generally, the Navy repair pipeline is shorter than commercial repair. This time saving plus the lower "cost" at NARFs, result in ASO's high use of Navy repair. The scrap pipeline, in steady state, carries $\alpha(a + bt + X)$ items from users and β_N(WNR) and β_C(WCR) items from repair facilities, where α equals

customer attrition, $\beta_{N,C}$ equals one minus the repair survival rate (Navy, commercial), and WNR, WCR are Navy and commercial repair inductions respectively. The resistor-like expansion joints in the pipelines represent the associated uncertainties of the customer demand rate (a + bt + X), carcasses return rate (1 - α), procurement lead time (PLT), Navy and commercial repair turn-around-times (NRTAT, CRTAT), induction delay (INDD), and carcass survival rate (1 - β).

To further understand the pictoral model, it is interesting to note its operation for a consumable item, which is equivalent to a repairable item when α, the customer attrition rate, is set to one. In this case, material enters the system by procurement at provisioning, and customer demands are pulled from RFI stock. When an item fails, it is automatically scrapped. In steady state, or statistical equilibrium, procurement of new items must be sufficient to replace all scrapped items. The consumable system must account for stochastic demand and hence is characterized by the probabilistic concept of risk of stockout in a procurement lead time. On the other hand, the repairable item has α equal to something less than one, and the non-attrition items are returned to NRFI stock, in queue for repair. To support equal demand for a consumable ($\alpha = 1$) and repairable ($\alpha < 1$) item it is evident that less procurement of new items is needed for the repairable item. Procurement of new repairables are needed only to replace items lost to customer and

repair attrition and to support increases in total system demand. In the limiting case, where no items are scrapped by the user or during repair and none are lost in the system, no procurement is required for a fixed demand level. Obviously, the limiting case is only of academic interest.

With cognizance of the descriptive analysis of the Repair/Procurement Interface Model, it is possible to identify certain characteristics of and principles for operating the system. First, it is assumed that the objectives of the interface are to minimize cost of operation and to minimize backorders.

Optimal operation of the system requires provisioning, steady state support, and termination at obsolescence. Provisioning the system must provide end use requirements and pipeline support. Steady state support requires procurement action to replace total attrition. Finally, when technical obsolescence is forecasted, or the supported weapon system is to be removed from operation, procurement of new items must be terminated so that the last demand is filled by the last repaired NRFI carcass so that stock levels are zero. Needless to say, the stochastic nature of the system prevents optimal operation, so policies must be established to operate within acceptable limits.

The basic principles for operating the system stem from what is termed the "substitution policy". This policy, described by Schrady (Ref. 8), "supplies one hundred percent of requirements from current RFI assets and repairable

carcasses until the supply of NRFI, in stock and in repair, decreases to a point where there are insufficient carcasses on hand to 'insure availability' of RFI material when it is required. This policy minimizes the RFI inventory, rather than NRFI inventory, and hence minimizes the opportunity cost of holding material."

The substitution policy states that procurement decisions must be timely, to insure the availability of RFI material when it is needed. The stochastic nature of repair survival and demand make the insurance of availability a probabilistic requirement. This implies the need for a variable safety level which depends upon a distribution of demand minus carcass regenerations. In other words, an attrition distribution over the procurement horizon is needed. The uncertainty of stochastic attrition permits two system states associated with the timeliness of procurement receipts. First, if attrition increases greatly, a receipt of an economic order quantity may not arrive in time to fill existing requirements. This will result in backorders. The hedge against these backorders is selection of a sufficiently low acceptable risk which will require greater investment, but decrease the probability that PLT attrition is equal to or greater than PLT assets. Second, if system attrition decreases markedly, the case arises where a procurement receipt will arrive before system RFI assets and NRFI assets are zero, causing increased holding costs. In this situation, it is obvious that repair decisions should be delayed, for a time, until the extra RFI assets are issued.

A "cyclic system repair requirements determination" assumption is compatible with the substitution policy. "CSRRD" operating in a stochastic system requires that a distribution of RTAT requirements minus assets be developed. Given such a distribution of the difference between RTAT requirements and assets, it is possible to set repair policy by specifying protection requirements. The significance of this protection is the probability that the induction quantity of carcasses, factored by survival rate, plus RFI on hand, will be sufficient to cover requirements over the RTAT. Obviously, the distribution of the difference must be a function of the uncertainty of demand over RTAT. Working backwards, if carcasses are not available for repair, or if NARFs are unable to induct for lack of capability, then the associated risk of not covering requirements during RTAT could be ascertained. This would be helpful in quantifying the impact of budget cuts and lack of NARF support. The availability of the RTAT requirements minus assets distribution provides for a variable safety level for the repair problem.

Another interesting situation, and perhaps the most subtle one of the Repair/Procurement Interface, is the state when, looking at requirements over the procurement horizon, a procurement is not justified, but, in fact, backorders exist. This situation could arise if random regenerations decrease suddenly, or if carcass returns fall off suddenly. However, over the PLT horizon, backorders will be filled from repair subject to the protection afforded by repair. The

point is that in a stochastic Repair/Procurement system, a backorder does not imply a buy requirement. In fact, the practice of "buying your way out of a hole" results in long supply and therefore an unnecessary investment and holding cost. Indeed, by the time the procurement is received, the backorder would have been filled by repair. The principle that repair money is always "justifiable to the budget", subject to supportive demand, and the availability of carcasses, follows from the above case. If this were not the case, the fixed costs of establishing and maintaining a Navy repair capability could not be justified.

The existence of INDD, or induction delay, in the model implies an additional principle of repair management. When induction delay is projected to be such that INDD plus NRTAT is greater than CRTAT, it is desirable to weigh the relative costs of Navy repair with commercial repair. If high level requirements exist for the item in question, then it would be advisable to ship it to commercial repair. This assumes that the commercial repair capability exists and also that the DOP (Designated Overhaul Point) "response to repair requests", proposed by B08, comes to fruition. These NARF responses would project when repair capability is expected, hence aid the decision to repair required carcasses commercially, and thus provide a tool to decrease time-weighted shortages.

Finally, analysis of the Repair/Procurement Interface is not complete without mention of system constraints. Such

constraints include compartmented budgets, such as commercial or Navy repair, procurement, operations and personnel budgets. Item procurement and repair is further constrained by limited personnel, support equipment, time and warehouse space, training and documentation. In a multi-item system there is obvious competition for limited resources. Decisions to invest in procurement and/or repair of one item are coupled with opportunity cost of not having the funds or resources for other items. These constraints make cost effective operation depend upon "budget execution" and repair decision restraints. Deferral of procurement and repair decisions implies a lower immediate protection, but enhances readiness by providing the ability to respond to priority contingencies with "spot buys" and repair overrides. The UICP tool for budget execution is recomputation of the shortage cost parameter, which is applied uniformly to all items in a cog. Currently ASO uses "levels" of requirements to constrain repair. The usefulness of the policy which determines the maximum "level" to be repaired is that it limits NARF inductions to cover high priority backorders or planned requirements. This insures use of limited resources to repair "certain" requirements and prevents the very great cost and potential waste of repairing all items for, say, sixty day stochastic demand. The proposed model should provide similar resource allocation constraints while providing the inventory manager with a feedback on the potential system impact of limited budgets and repair capability.

To conclude this section, the Repair/Procurement Interface is a delicate operation. Like dual carburators, it requires proper timing and proper tools to tune it. The next section is a proposed model which presents the conceptual framework for accomplishing an effective UICP Repair/Procurement Interface. It is consistent with basic Supply Demand Review and Cyclic Repairables management techniques.

B. THE PROPOSED MODEL

The Repair/Procurement Interface is probabilistic and requires the solution of two sub-problems. Unlike a consumable item, computation of a repairable item procurement policy requires knowledge of repair regenerations during the PLT horizon. The timeliness of procurement decisions must depend upon the demand rate and carcass regenerations over the procurement horizon. On the other hand, the repair problem, with horizon equal to RTAT, must be aware of when due-in procurements will be received. The following sections present the procurement and repair problems.

1. The Procurement Problem

The procurement problem of the proposed model is similar to the existing D05 computation. In fact, the only differences are that average annual demand and mean PLT demand are replaced by average annual attrition and mean PLT attrition; and that the distribution of PLT demand is replaced by the distribution of PLT attrition. The new distribution of PLT attrition is obtained by convoluting the distributions of PLT demand and regenerations. The PLT attrition distribution is important because it represents procurement knowledge of stochastic repair. The procurement problem generates procurement policies. The policies are an economic order quantity (Q_p), a reorder level (r_p) and a Supply Demand Review like rule for when to order. The last requirement, for a reorder rule, appears contradictory with the usual concept of a reorder level, but because protected

items (a') represent non-attrition demand, they must be added to r_p to get the system reorder point.

To compute Q_p and r_p, Hadley and Whitin's (Ref. 4) assumptions for the approximate treatment of the continuous review model hold. The objective function is to minimize the total average annual cost of ordering, holding, and being short. Under the "substitution policy" it is necessary to procure material to replace PLT attrition, where attrition is the difference between demand and regenerations, and to provide safety stock for potential demand variability. The objective function follows from Hadley and Whitin with the following changes. The total cost expression uses average annual attrition in place of average annual demand. Mean PLT demand is replaced by mean PLT attrition. The other major difference is that the distribution of PLT attrition is used, instead of the distribution of PLT demand, to compute the reorder level (r_p).

Before presenting the derivation of the attrition distribution it is noted that the economic order quantity (Q_p) is computed in a manner similar to D05. For computational convenience, the attainment of Q_p and r_p is uncoupled, preventing the need for an iterative solution. To this end the expected backorder term is dropped from the expression for Q_p. The result is that Q_p is equal to the Wilson or economic order quantity, except that average annual attrition is used vice average annual demand. The formula is:

$$Q_p = \sqrt{\frac{2\lambda_{ATT} A}{IC}} \qquad (1)$$

where: λ_{ATT} = average annual attrition

A = cost of placing orders

I = holding rate

C = procurement cost

The formula for computing the reorder level, r_p, is developed by taking the partial derivative of the total cost expression with respect to r_p. The resulting expression is set equal to zero and solved for $H(r_p)$, with the following result:

$$H(r_p) = \frac{ICQ_p}{(\lambda_{ATT})\pi + ICQ_p} \qquad (2)$$

where: $H(r_p)$ = the complementary cumulative of the distribution of attrition in PLT = Risk

π = stockout cost

Q_p = economic order quantity

λ_{ATT}, I, C are as above

Given the above expression for risk, the CARES generated stockout cost, and the distribution of PLT attrition, it is possible to compute r_p. CARES is the existing UICP analyzer which functionally assigns an acceptable stockout cost, by cog, to help the inventory manager stay within assigned budgets. And so, it remains to derive the distribution of PLT attrition.

Three things were needed to derive the required distribution of the random variable PLT attrition, $X_{ATT(PLT)}$. First, PLT attrition was defined as:

$$X_{ATT(PLT)} = a + b(PLT) + X_{PLT} - Z_{PLT} \qquad (3)$$

where: $X_{ATT(PLT)}$ = random attrition in PLT

a = constant demand in PLT

$b(PLT)$ = PLT demand which is a linear function of time

X_{PLT} = gross system random demand in PLT

Z_{PLT} = random carcass regenerations in PLT

Second, realizing that a and b(PLT) are known demand (zero variance), it is necessary to assume a distribution for X_{PLT} and Z_{PLT}. Three assumptions are tractable for purposes of this derivation. Both demand and regenerations can be assumed to be distributed as Poisson, gamma or normal random variables. It is of academic interest to note recent Naval Postgraduate School studies that indicate the desirability of the gamma distribution because it is non-negative and flexible. However, the normal distribution will be assumed because it is consistent with current UICP practice.

Third, to attain the distribution of $X_{ATT(PLT)}$, theorem 9B from Parzen (Ref. 5) was useful. The theorem states, "Let X_1 and X_2 be independent random variables. Then if X_1 is normally distributed with parameters m_1 and σ_1 and X_2 is normally distributed with parameters m_2 and σ_2, then $X_1 - X_2$ is normally distributed with parameters

$m = m_1 - m_2$ and $\sigma^2 = \sigma_1^2 + \sigma_2^2$". A similar convenient theorem exists for Poisson and gamma assumptions. It is also useful to note that if X is distributed normally with mean m and variance σ^2; then X + a (a in the set of real numbers) is distributed normally with mean m + a and variance σ^2.

To finally attain the distribution of PLT attrition it is necessary to argue the independence of PLT demand and PLT regenerations. The condition of independence is determined by the inherent nature of the random variables. PLT demand is determined by user operations schedules, equipment population, operations and environment, and technician proficiency. However, the number of regenerations in the same PLT is dependent upon available carcasses, shipping delays, repair capability, and piece part availability, besides past demand. Only past demand is generic to PLT regenerations. The influence of demand in the same PLT is considered small, particularly for demand levels appropriate for the normality assumption. Hence, the independence assumption is made with some confidence.

With the above tools, the distribution of PLT attrition is finally in hand:

$$X_{PLT} \overset{d}{\sim} \eta(\mu_{X(PLT)}, \sigma^2_{X(PLT)})$$

$$Z_{PLT} \overset{d}{\sim} \eta(\mu_{Z(PLT)}, \sigma^2_{X(PLT)})$$

$$X_{ATT(PLT)} \overset{d}{\sim} \eta\left(a+b(PLT)+\mu_{X(PLT)}-\mu_{Z(PLT)}, \sigma^2_{X(PLT)}+\sigma^2_{Z(PLT)}\right) \quad (4)$$

The distribution of $X_{ATT(PLT)}$ is now determined so that r_p can be computed. What remains is to determine the decision rule for placing an order.

The rule for timing the procurement decision follows from the current Supply Demand Review technique. That is, compare PLT requirements minus assets and when equal to or greater than zero, place an order for Q_p plus the difference. The following equation describes the decision rule:

$$\text{if} \quad \underbrace{\left(a' + r_p\right)}_{\text{PLT Requirements}} - \underbrace{\left(RFI + (1-\beta)NR + (1-\beta)CR + \bar{Z}_{(PLT-RTAT)} + \delta_{PLT}Q_p\right)}_{\text{PLT Assets}} \geq 0 \Rightarrow \text{procure} \tag{5}$$

where:

a' = protectable assets (PWRS)

r_p = reorder level calculated using (1), and representing attrition requirements during PLT

RFI = RFI on hand at review time

$(1-\beta)$ = carcass survival rate

$\left.\begin{matrix} NR \\ CR \end{matrix}\right\}$ = carcasses in Navy repair (NR) and commercial repair (CR)

$\bar{Z}_{PLT-RTAT}$ = expected regenerations in PLT-RTAT

$\delta_{PLT} = \begin{cases} 1 \text{ if expect to receive } Q_p \text{ in PLT} \\ 0 \text{ if otherwise} \end{cases}$

Q_p = economic order quantity

The PLT requirements expression $(a' + r_p)$, called reorder "point" in B10, includes reservation requirements plus r_p which represents sufficient stock to cover acceptable

protection for end use demand (a + bt + X). But the PLT assets expression requires some explanation. The RFI term is straight forward, $(1 - \beta)$ (NR or CR) is the regenerations due in PLT from items already in repair, and $\overline{Z}_{PLT-RTAT}$ is expected regenerations due during PLT - RTAT. The reason that the later potential assets, $\overline{Z}_{PLT-RTAT}$, are only computed over PLT - RTAT is that carcasses received in NRFI stock in the last RTAT days of PLT, on the average, will not be out of repair in time to count them as RFI assets in PLT. The $\delta_{PLT}(Q_p)$ term counts Q_p RFI assets if a previous EOQ is due-in during PLT, otherwise δ_{PLT} is zero and hence Q_p is not counted. Naturally, this term could be $n \cdot Q_p$ if n past orders are due-in during PLT.

Thus, to summarize, the procurement problem provides an economic order quantity (Q_p), a reorder level (r_p) and a decision rule for when to initiate or recommend procurement action. To repeat, the development of a PLT attrition distribution represents a mechanism for establishing the interface of repair and procurement. The distribution provides information to insure a timely procurement decision.

2. The Repair Problem

The repair problem must specify when and how much to repair. There are some basic differences between repair decisions and procurement decisions. First, the repair horizon is RTAT, either NRTAT or CRTAT, as appropriate. RTAT is significantly smaller than the procurement horizon and therefore the repair decision is made with more certain

information about potential regenerations. Specifically, over the repair horizon only NRFI carcasses already in repair, times the repair survival rate, can be counted as RTAT assets. Regenerations over RTAT can be treated deterministically contrasted to the need to depend upon a distribution assumption and smoothed historical data for regenerations over PLT. Thus, the only random variable in the repair problem is gross system random demand.

The following proposed model for the repair problem is consistent with the method advocated in Naval Material (NAVMAT) Instruction 4400.14A, Navy Repairable Management Manual (Ref. 2). The method is known as the repetitive repair requirement computation system. Operationally, it specifies that total system requirements for each item be recomputed by urgency of need during each requirement review cycle. The method requires, further, that material actually in repair, or scheduled for repair be used in determining the induction requirements and priorities for induction of additional material for repair.

The basic concept for the proposed model, follows from B08, which complies with the intent of the NAVMAT instruction and is consistent with the "Cyclic System Repair Requirements Determination" assumption. However, the proposed model extends the expected value model of B08, and introduces a distribution of RTAT demand. The distributional assumption provides a variable safety level concept for repair. It should be emphasized that the proposed system

models the ICP's role in the repair program, which does not interfere with the NARF's ability to "batch" repair if they are able to realize fixed cost economies.

The decision rule for the repair problem is: compare RTAT requirements plus Repair Safety Level (RSL) minus RTAT assets and, when there is a positive difference, ship to commercial repair or recommend for induction the difference times the inverse of the repair survival rate; constrained by the designated overhaul point (DOP) maximum induction quantity or NRFI carcasses available at the DOP (not already in repair and/or scheduled for repair). The Repair Safety Level (RSL) is associated with a desired risk. For the repair problem, risk is equal to the probability that RTAT requirements plus RSL minus RTAT assets is equal to or greater than zero, or the probability of a stockout in RTAT. To obtain the associated risk and appropriate RSL it was necessary to derive the distribution of the RTAT difference between requirements and assets, called the random System Repair Requirement (X_{SRR}).

It was again assumed that RTAT gross system demand, X_{RTAT}, was distributed normally ($\mu_{X(RTAT)}, \sigma^2_{X(RTAT)}$). Then:

$$\begin{aligned} X_{SRR} &= \text{RTAT requirements minus RTAT assets} \\ &= a' + a + b(RTAT) + X_{RTAT} - RFI - (1-\beta)NR \\ &\qquad - (1-\beta)CR - \delta_{RTAT} Q_p \end{aligned} \tag{6}$$

where: a' = protectable demand

a = backorders and one time planned requirements due during RTAT

$b(RTAT)$ = planned requirements due today and every day of RTAT

X_{RTAT} = random gross system demand

RFI = RFI stock on hand at review time

$\left.\begin{matrix}(1-\beta)NR \\ (1-\beta)CR\end{matrix}\right\}$ = carcass survival rate times carcasses in Navy repair (NR) and commercial repair (CR)

$\delta_{RTAT} = \begin{cases} 1 \text{ if } Q_p \text{ due-in during RTAT} \\ 0 \text{ otherwise} \end{cases}$

Q_p = economic order quantity

Thus, the distribution of X_{SRR} is of the form X + "a", where "a" is a real number which represents all of the terms above except X_{RTAT}, and is, by previously mentioned theorem, distributed as follows:

$$X_{SRR} \overset{d}{\sim} \eta\Big(a' + a + \frac{b(RTAT)}{2} + \bar{X}_{RTAT} - RFI - (1-\beta)NR - (1-\beta)CR - \delta_{RTAT}Q_p \, , \sigma^2_{X(RTAT)}\Big) \tag{7}$$

where: a', a, RFI, $(1-\beta)NR$, $(1-\beta)CR$, $\delta_{RTAT}Q_p$ = constants

$\frac{b(RTAT)}{2}$ = average linear planned requirements during RTAT

$\bar{X}_{RTAT}$ = average gross system demand during RTAT

$\sigma^2_{X(RTAT)}$ = variance of demand in RTAT

So, the random variable system repair requirements, X_{SRR}, is distributed normally with mean and variance as in equation seven, call them $\mu_{X(SRR)}$ and $\sigma^2_{X(SRR)}$.

Thus, given the distribution of X_{SRR} and an acceptable risk, the required repair problem decisions are determined. The rule is, when RTAT requirements plus the Repair Safety Level are equal to or greater than RTAT assets, ship or recommend induction of the difference times $1/(1-\beta)$; subject to NARF induction and carcass availability constraints.

$$f(X_{SRR}) \overset{d}{\approx} \eta(\mu_{X(SRR)}, \sigma^2_{X(SRR)})$$

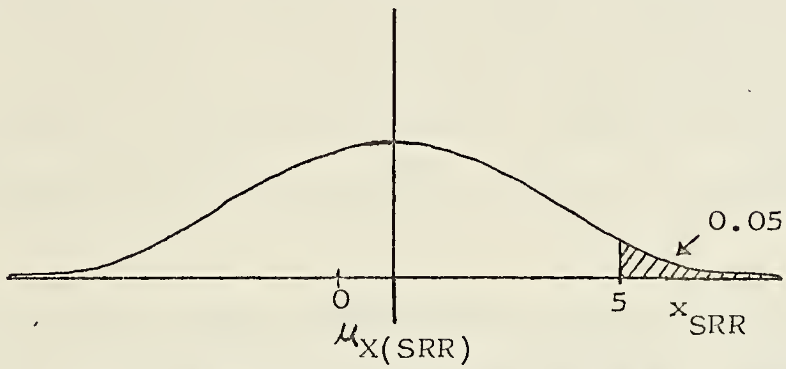

Figure 2. The Distribution of System Repair Requirements

Assuming that the above represents the distribution of system repair requirements, it is possible to develop an understanding of the meaningfulness of the item Repair Safety Level (RSL) and risk. In the current expected value formulation, an undeterminable risk is implied because the Repair Safety Level is arbitrarily set at zero. The proposed model adds a variable Repair Safety Level. The example in Figure 2 shows that, to obtain a risk of 0.05 for this item, a Repair Safety Level of five units must be used. This means that when RTAT requirements plus five units are equal to or greater than RTAT assets, ship or

recommend repair of the difference times $1/(1-\beta)$. It is worthy to note that if a negative Repair Safety Level exists then backorders must exist before repair action is taken. This situation models the current repair system where only high priority backorders and planned requirements are being repaired. It is of further note that the risk determined as above would be underestimated if a sudden loss of capability developed or if demand surged, but it appears to be the best risk available with limited information. Really, the resulting risk is no better than the demand distribution assumption, demand parameter estimation, and the smoothed value of the carcass survival rate. After all, risk is a "probabilistic" concept.

The above repair model would provide the repair manager with a tool for stratifying repairable items by risk categories. A report generator could be developed which prints out a risk frequency distribution of the total repairable inventory, or by demand levels called Marks. The frequency distribution would identify to the decision maker a stratification of the status of the repair system and would serve as a tool for budget justification. The proposed model would assist an intensified management program for fast movers or high dollar value items by providing weekly item risk status. Naturally, high interest items with negative Repair Safety Levels would be prime candidates for dollar investments.

To conclude this section, the above procurement and repair problems follow from the "substitution policy" and "cyclic system repair requirements determination" assumption. The proposed model is consistent with current Supply Demand Review and Cyclic Repairable Management applications. The proposed model, however, provides a more adequate computation of procurement policies; adds a variable safety level capability to repair policies; and effects an "interface" by providing procurement knowledge of repair and vice versa.

IV. CONCLUSION

The paper presented an analysis of the existing UICP model, a description of the nature of a Repair/Procurement Interface for repairable item management, and a proposed model.

The primary findings of the analysis of the existing UICP model were that there is a major contradiction between D05 and B08 and that there does not exist an interface between the procurement and the repair problems.

An iconic model was developed which models a proper Repair/Procurement Interface. Under a "substitution policy" and a "cyclic system repair requirements determination" assumption, characteristics of the interface were noted and principles of operation were developed. From these principles, a proposed model was conceived which provides equations and decision rules to obtain procurement and repair policies. The proposed model enriches the UICP capability by incorporating procurement knowledge of repair regenerations and providing a variable safety level capability for the repair problem. The variable safety level capability has budget justification possibilities.

The proposed model is divided into two problems. The procurement problem compares procurement lead time horizon requirements against assets. When procurement lead time assets are less than the reorder point, then an order for

the economic order quantity plus the difference is recommended. The economic order quantity and reorder level are computed using similar equations as D05. The repair problem, on the other hand, compares repair turn-around-time requirements plus the Repair Safety Level to repair turn-around-time assets. When there is a positive difference, a repair action is recommended. The repair computation is consistent with current Cyclic Repairable Management, B08, techniques and the comparison of horizon requirements against assets is consistent with Supply Demand Review, B10.

It is believed that the results of this analysis are of potential application to the real-world. For instance, it is recommended that UICP application D05 repair problem computations be turned off; that a variable safety level model be implemented for the repair problem; and that a procurement lead time attrition distribution replace the procurement problem distribution in application D05, Levels Computation.

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The U.S. Navy inventory control of repairable items at the Inventory Control Point level is accomplished with the aid of the Uniform Inventory Control Program. This paper analyzed the existing Uniform Inventory Control Program's implied repairable model. Also, the nature of a Repair/ Procurement Interface for management of repairable items

was analyzed. Under a "substitution policy" and a "cyclic system repair requirements determination" assumption, characteristics of the interface were noted and principles of operation were developed. From these principles, a proposed model was conceived which provides equations and decision rules to obtain procurement and repair policies.

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